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MUON BEAM POLARIZATION AT THE LAMPF BIOMEDICAL CHANNEL

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Summary

Recent modifications to the LAMPF Biomedical Channel[1] have improved versatility for stopping pion and muon physics experiments. High muon polarization was achieved by favorable kinematic selection of the decay muons. This polarization has been measured and found to be close to the design expectation of about 85%. The Hanle method[2] was employed to measure the polarization by observing left-right decay asymmetry at right angles to the beam with small precession fields (0-50 gauss). This technique is particularly suitable for high-intensity muon beams.

Introduction

The muon beam polarization has been measured for backward-decay tunes previously reported[1]. Comparison is made between these measurements and design calculations carried out with the program TURTLE[3] containing a modification for estimating polarization. The Hanle method[2] for polarization measurement was found to be effective and easy to implement.

Description of Backward-Decay Configuration

The first section of the channel focuses a dispersed beam at the momentum dispersion plane D and slit S2 indicated in Figure 1. Muons are collected from pion decays in the region between B2 and B3 and the first portion of B3. Elements B3 and Q4 provide momentum analysis of the backward-decay muons; a momentum dispersed image of slit S2 is formed between Q4 and Q5. The slit S3 at this second bend-plane focus selects the momentum bite of the analyzer. The slit S2 limits the source size for the analyzer as well as the momentum spread of the pion beam producing the muons. The tightest constraint available for obtaining muons of high polarization is a narrow momentum cut on muons which are derived from a pion beam with a small momentum spread. Both constraints are realized with small slits S2 and S3. In both calculations and experiment a large improvement in polarization was found by tuning the analyzer on the low momentum side of the backward momentum peak, and so the analyzer was set for maximum rate.

Calculation of Average Beam Polarization

Polarization was estimated with TURTLE[3] modified to include calculation of the polarization along the direction of motion of the muon in the laboratory frame[4]:

[illegible]

Here $\vec{P}$ is the polarization vector, P_μ and E_μ are the muon momentum and energy in the lab (P_μ^* and E_μ^* are in the pion rest frame), and $\gamma_\pi = E_\pi/m_\pi$. The polarization

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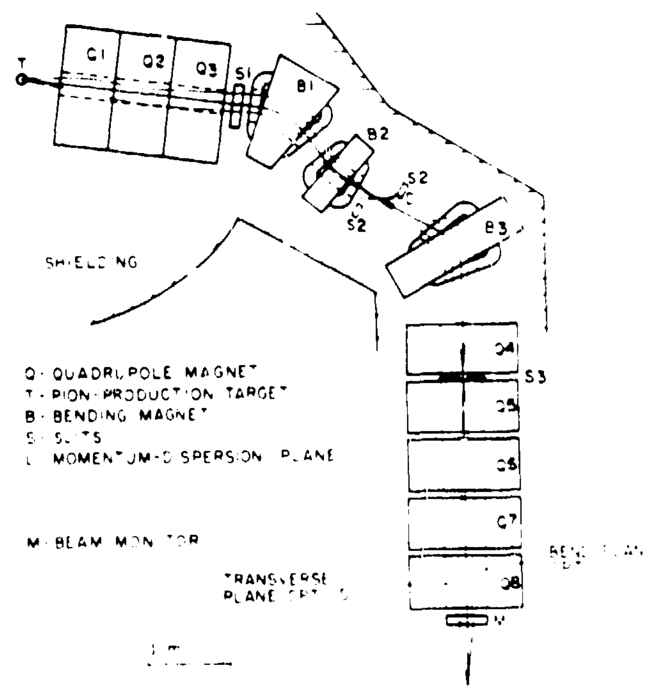

Fig. 1. LAMPF biomedical channel configured for backward-decay muon beams. The decay region is between B2 and B3 and extending inside B3.

vector $\vec{P}$ is determined by this cosine with respect to the muon direction and an azimuthal decay angle. The polarization vector $\vec{P}$ of each accepted muon is projected on to the channel central axis and then averaged over all muons. The resulting average, taken at the channel exit, is the beam polarization along the axis; in general the beam polarization itself will not be aligned with the central axis.

Muons from decays within B3 are not properly momentum analyzed and give rise to the following complicating effect: Within B3 pions follow a path of large radius and produce muons that travel toward the inside of the arc that can be accepted by the system and introduce an asymmetry in the bend plane of the channel (as well as reduce polarization). That is, muon angles in the pion rest frame toward −X are preferred. As a result, the muon beam acquires a net "X-component" of polarization which is directed toward +X. This occurs because the negative helicity of the μ^+ in the pion rest frame is reversed in the lab for backward decays while the component perpendicular to the original pion velocity is not reversed. Muons originating in the drift region also have a positive X-component of polarization due to the fact that pions there have an average positive X' slope of 20 to 30 mr. Therefore muons are preferentially accepted with negative decay angles in the pion rest frame which give them a smaller angle to the central axis and a larger acceptance.

At the channel exit, the polarization components along each axis are the average projections of the polarization vector $\vec{\zeta}$. These are $\zeta_x = 0.16$, $\zeta_y = 0$, and $\zeta_z = 0.87$. It is assumed that $\vec{\zeta}$ has not precessed around the muon direction while traversing the channel from the point of pion decay. The resulting calculated beam polarization is 0.88 and is tilted toward +X by 0.18 radians. The calculation also predicts improvement in polarization through collimation of the output beams where the higher momentum particles collected from within B3 are not well focused.

Polarization Measurements

Hanle Measurement Method

Hanle[5] observed magnetic depolarization of resonance fluorescence. The magnetization of vapors produced by polarized light was precessed by small magnetic fields perpendicular to the magnetization while the deexcitation radiations were analyzed and recorded. In the muon case, the system is "pumped" with the full muon stopping intensity available (up to 10^8 μ^+/sec during the pulse) allowing many muons to be present in the target at the same time. The stopped muons, polarized downward, produce the maximum observed decay positron right-left asymmetry at a transverse field B of about 6 gauss, which results in a muon precession of about a radian in one lifetime τ. A single counter telescope aligned at 90 degrees to the central axis of the channel will see a positron rate proportional to[6]:

$$1 - aP\left[\frac{\omega B\tau \cos\phi}{1+(\omega B\tau)^2} + \frac{\sin\phi}{1+(\omega B\tau)^2}\right] \qquad (1)$$

Here a is the muon decay asymmetry equal to 1/3, P is the polarization of the stopped beam in the graphite target which we take to be the polarization of the beam itself, the precession angular velocity is ωB, and ϕ is the angle between the polarization vector and the central axis. The first term, known as dispersive, is dominant and represents the signal from the polarization component along Z; the second, absorptive, term is due to the polarization component along X. The general shape of the function is seen in Fig. 2.

Experimental Setup

The Hanle method was employed because of the ease of the experimental setup, requiring only a coil and a few counters. Figure 3 shows two counter telescopes viewing the graphite target at right angles to the vertical central axis. Fortunately the counters were placed in the bend plane of the channel rather than perpendicular to it. Although it was realized that the polarization was affected by unfavorable decays in the third bend B3[1], it was not appreciated before the experiment was run that the polarization vector of the beam would be rotated in the bend plane, giving rise to differences in the Hanle signal between positive and negative fields, i.e., non-zero ϕ in Eq. (1). (See Fig. 2.) We did not allow for rotation of the setup about the vertical axis, contrary to the general recommendation to do so for asymmetry experiments. A rotation of the apparatus by 180 degrees would have shown the effect to be in the channel rather than in the apparatus.

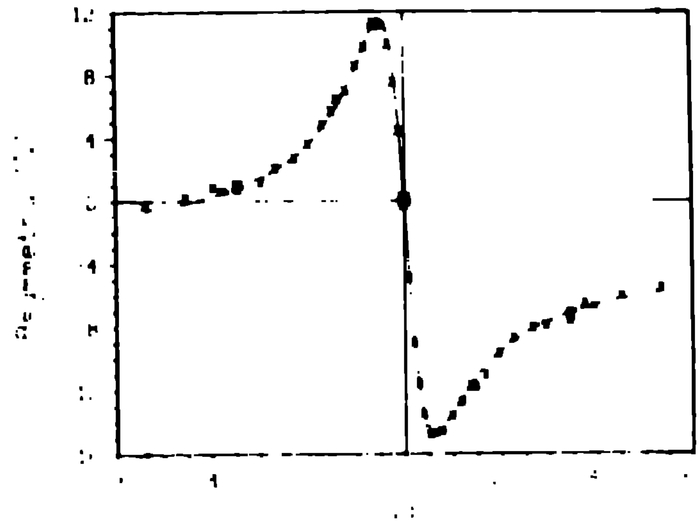

Fig. 2. Experimental data and fitted function for the asymmetry 12-34/12+34 as a function of the transverse magnetic field B. A positive asymmetry means that more counts are present on the +Y side of the channel.

The collimators and target, each 12x12 cm, were sized to accept as large a transverse fraction of the beam as reasonable since TURTLE gave lower polarization for the tails of the X and Y beam profiles. The graphite target thickness of 1.4 g/cm² stopped about 9% of the beam. Not all of the high-momentum tail is stopped in this target; however the target is representative of what might be used in an experiment.

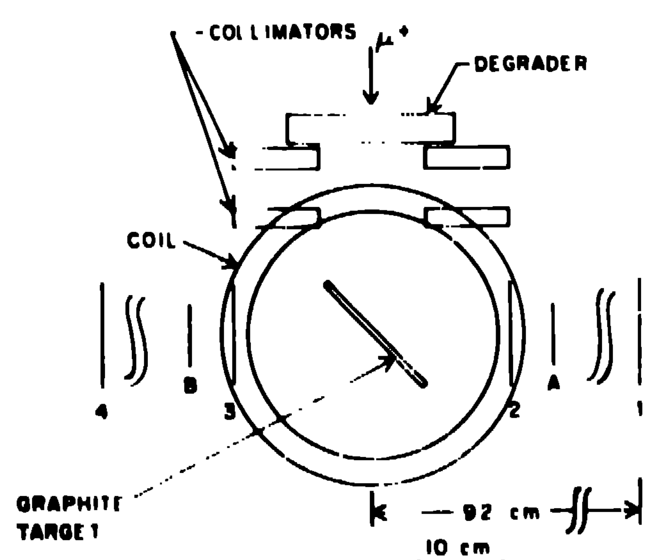

Fig. 3. Geometry for measurement of beam polarization. 83 MeV/c μ^+ enters from above, traverses 3.6 cm polyethylene degrader, is collimated with Cerrobend pieces, and enters an ATJ graphite target. Asymmetries 12-34/12+34 and 12A-34B/12A+34B are measured as a function of the field B. Counters 1 and 4 are located each 92 cm from the beam axis. Counters are 1/16 inch thick. Counter 1 is on the +X side of channel, and positive field B is along +Y or out of the paper and precesses μ^+ toward -X giving negative asymmetry.

The slanted target introduces considerable right-left solid angle difference for the triple coincidences, those including counters A and B. Although there is no problem in the analysis of this data, a symmetrical design would have been more suitable.[6]

Analysis of Measured Asymmetries

The complete treatment of the Hanle method and data analysis was carried out by Roesch et al. as part of a muon capture experiment.[6] They developed a function for the asymmetry between right and left counters based on Eq. (1), (where the overall sign is reversed for the telescope on the −X side of the channel). The right/left count ratios are normalized to the count ratio at B=0, accounting for the differing solid angles on the two sides. The usual asymmetry is then formed from the normalized ratios. The resulting fit to their functional form gives for the 12−34/12+34 asymmetry

$$aP = -26.3 \pm 0.10\%$$

$$\xi = -0.122 \pm 0.002 \text{ radians.}$$

This result is derived from the data with a double coincidence on each arm. The negative sign only reflects our choice of direction for positive B. The fitted curve is shown in Fig. 2. The corresponding fit to the 12A−34B/12A+34B asymmetry, not shown, is

$$aP = -28.[illegible] \pm [illegible].16\%$$

$$\xi = -0.116 \pm 0.002 \text{ radians.}$$

This result comes from the data with a triple coincidence on each arm. The muon lifetime is fixed in these fits. Variation of the muon lifetime alters the fitted aP by a factor 0.99%, and the fitted lifetime is 3% low. The target-out background correction is 1.03 for the doubles data and 1.012 for the triples, giving beam polarizations of:

$$P \text{ (doubles data)} = 81\%$$

$$P \text{ (triples data)} = 85\%.$$

Although the statistical error for this procedure is only 0.5%, some comment is necessary. The triple coincidence polarization is higher as expected because of the restricted view of the target, effectively collimating the incident beam. So at least for this beam, the polarization is highly dependent on the phase space actually observed, and a single quotation is not sufficient. However, the Hanle method is capable of precision measurement of polarization for a given geometry of collimators and target.

To check that the sign of the angle ξ is consistent with the TURTLE prediction, notice that a component of polarization along +X will induce a positive asymmetry in the signal near B=0 due to the μ^+ decay asymmetry. The effect of this absorptive term goes to zero at large B. So the signal is increased for small B and unaffected at large B. But since all data are normalized at B=0, the overall effect is to reduce the signal uniformly at large B, reduce the signal less and less as B is reduced, and force the signal to be zero at B=0 which is exactly what is seen in Fig. 2. The argument is independent of the direction chosen for positive B. The measurement is not sensitive to a net Y component of polarization.

Corrections to the decay asymmetry $\bar{a}$ due to positron scattering were sought with a target of half the normal thickness. The aP values increased by factors 1.025 for the doubles data and 1.016 for the singles. This effect is however attributed to improvement in P rather than change in $\bar{a}$. The higher-momentum muons are not stopped by the thinner target, and these are just the ones with lower polarization, as they come from within B3. The triples data already exclude some of these muons as described earlier, and so the effect should be smaller. As a verification, a Monte Carlo simulation was done for a simple geometry with the muon spin along the axis of the telescope. All positron processes in the target are handled by this code, although the effect of the field on outgoing positrons was not included. No significant deviation from a=1/3 was found.

An interesting experimental test related to positron scattering and absorption was done with 2" thick Al blocks located in the path of the positrons in front of Counter 1 and in front of Counter 2. Attenuation of lower energy positrons resulted in a 50% increase in the effective decay asymmetry $\bar{a}$ for 60% reduction in counting rate.

Conclusion

Agreement between measured and calculated polarization is not completely satisfactory. Low measured polarization could be caused by unexpected loss of polarization in the graphite or some other correction to $\bar{a}$. A high calculated polarization could be caused by an imperfect modeling of acceptance in TURTLE. The agreement for the rotation of ξ is only qualitative, and the difference is not understood. Longitudinal fields, such as those at the exit of B3, will rotate to some extent ξ around the muon direction. Clearly a more general approach to polarization calculation is necessary, particularly if the orientation of the beam polarization is important.

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